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Research

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Fracture Toughness Evaluation of Asphalt Mixtures Containing Rubber Powder and Steel Slag at Low Temperature

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ABSTRACT

Pavements are part of the most important structure of the roads and a huge amount of money is spent on their repair and improvement every year. If special measures are used in the mixing plan of these procedures, most of which are made of asphalt mixtures, millions of dollars can be saved annually. On the other hand, in recent years, in addition to paying attention to increasing the life of asphalt mixtures, special attention has been paid to the use of recycled materials and materials to improve the life of asphalt pavements, because this work has environmental advantages in addition to economic benefits. Therefore, in this research, the cracking resistance of asphalt mixtures containing two recycled materials, steel slag and rubber powder has been investigated. Cracking resistance has been investigated using fracture toughness in two loading modes, one and two pure, at two low temperatures of -12 and -24. The results of this research showed that the use of steel slag (50 and 100 percent) and rubber powder (5 and 10 percent) can be investigated and loaded in both cases to improve the fracture toughness of asphalt mixtures. Meanwhile, the combination of both modifiers in the percentage of 5% of rubber powder and 50% of steel slag provides the most optimal amount possible.

Keywords: steel slag, rubber powder, fracture toughness, loading mode, low temperature

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1. INTRODUCTION

The lifespan of road paving is one of the most important parameters affecting the economy of a country. Therefore, one of the primary goals of designing and implementing asphalt paving on the road surface is to achieve the best performance in terms of durability and stability in optimal conditions. The quality of the pavement depends on various factors, including the constituent materials, including stone materials and bitumen [1-3].

Meanwhile, although bitumen is much less in terms of weight compared to stone materials, bitumen plays a very important role in the performance of asphalt pavements and the durability and stability of asphalt mixtures, and any change in the performance of bitumen causes many changes in the performance of asphalt mixtures. [4-5]. The changes in bitumen structure are done with the aim of modifying and improving bitumen properties, and it is mostly

focused on modification of bitumen with special additives. Among the materials that can be used for bitumen modification are: polymer-based materials, recycled materials and Nano-materials, each of which can be used depending on the main purpose of bitumen modification. Among these mentioned cases, recycled materials, while improving some properties of the mixture, also have many environmental benefits because it prevents the accumulation of waste materials and reduces environmental damage [6-8]. Rubber powder as a recycled material that can be used in asphalt was used in different researches in different ways. Rubber powder is usually based on rubber and tube and is usually used in wet or dry form to improve the properties of asphalt mixture [8-9].

On the other hand, steel slag is one of the side products of the steel industry, which contains valuable materials and compounds such as calcium oxide, magnesium oxide, iron, phosphorus, manganese and silicon in its components. Steel slag is not used directly and is accumulated as waste. Due to its huge volume, the depot of these materials, in addition to various limitations, can pose very serious environmental risks [10]. Steel slag is divided into electric arc furnace slag (EAF) and oxygen-based slag (BOS) [11]. High specific weight, angularity, hard surface texture, high strength and durability of steel slag are mentioned as one of the main factors for improving the mechanical properties of asphalt mixtures [12]. On the other hand, the increase of the optimum bitumen due to the high surface porosity of the slag and the increase of the empty space due to the use of coarse-grained slag has also been mentioned as one of the disadvantages of using slag in asphalt mixtures [13]. In the following, some of the researches carried out regarding these two substances are stated.

Mashan et al investigated the effect of rubber powder on the performance characteristics of asphalt mixtures and investigated the percentages from 6% to 20%. In this research, taking into account the volume characteristics, Marshall Resistance and modulus of elasticity, the value of 12% was determined as the optimal percentage of using rubber powder [14]. In a similar study, Katman et al. also introduced 12% as the appropriate value for rubber powder by examining the characteristics of permanent deformations [15]. Kalpa et al. investigated the effect of adding rubber powder as a replacement for fine-grained stone materials and

observed that adding rubber powder provided a better index in terms of permanent deformations, fatigue and moisture sensitivity. So that the investigated mixture has shown 64% improvement in permanent deformation, 6% improvement in fatigue and 36% improvement in humidity sensitivity compared to the control condition. The researchers of this research also investigated the economic impact of adding rubber powder and showed that adding rubber powder increased the cost by 3-4% per square meter, but it caused an average improvement of 20% during the useful life of the pavement [16]. Ameri et al investigated the effect of rubber powder and polyethylene terephthalate. The results of this research showed that the addition of polyethylene terephthalate increases the hardness of bitumen and thus increases the hardness of the mixture. Also, the addition of rubber powder compensates a part of the added hardness, and as a result, the use of polyethylene terephthalate and compound additives in asphalt mixtures can show a favorable result [17]. Li et al. investigated the effect of adding rubber powder and SBS polymer on the high temperature performance characteristics of asphalt mixtures. In this research, they investigated the effect of single and double addition of rubber powder-SBS and showed that with the increase in temperature from 50 to 70 degrees Celsius, the asphalt modified with the combination of rubber powder and SBS shows the least decrease in resistance. The researchers of this research suggested the use of a double additive of rubber powder and SBS instead of a modified mixture with rubber powder and SBS alone [18].

Goli et al investigated the rutting and moisture sensitivity of asphalt mixtures containing slag. The results of this research showed that the use of slag to replace stone materials has improved the rutting resistance, reduced moisture sensitivity and improved the fatigue life of asphalt mixtures [19]. Ghazizadeh et al also compared BOS and EAF slag using Marshall Resistance and fatigue life tests. The research results of these researchers showed that the use of EAF slag is much more suitable than BOS slag in asphalt mixtures [20]. By substituting steel slag at a ratio of 25, 50 and 75% instead of limestone aggregates, Zia et al performed experiments on aggregates and mechanical performance of asphalt mixtures. The results of this research showed that the use of slag has better results than limestone materials in parameters such as fracture percentage, Los Angeles wear, total index, surface texture and

percentage of non-compacted void space. On the other hand, the results of performance tests such as yield modulus also showed better performance of asphalt mixtures containing slag [21]. Shaker et al optimized fine and coarse steel slag based on the fracture toughness of asphalt mixtures at low temperature. In this research, the maximum coarse-grained slag is 100% and the maximum fine-grained slag is 50%. The results of this research showed that when the temperature decreases from zero to a certain limit, the value of the fracture toughness increases first and then decreases from a certain limit. Also, the researchers of this research did not hear that the use of fine-grained and coarse-grained slag should be selected according to the design temperature in such a way that at temperatures close to zero degrees Celsius, the use of only coarse-grained slag will have a higher failure toughness. Temperatures between

zero and -24, the use of a suitable combination of fine-grained and coarse-grained slag showed a better toughness [22].

According to statistics, every year millions of tire rings are collected and stored in the form of waste in the world after use, also millions of tons of steel slag are deposited near the steel factories as the waste material of the steel industry, both of which are both environmental and Due to the lack of space required for storage, it causes many problems. In this research, the use of asphalt mixture containing modified bitumen with rubber powder and stone materials replaced with steel slag has been investigated. The main purpose of the research is to investigate the fracture toughness of the new mixes made in the research under one, two and two low temperature loading modes of -12 and -24.

2. MATERIALS AND METHODS

2.1. Materials

Consumable bitumen has been used in this research as the main material for creating adhesion between stone materials and research additives. This bitumen is PG64-22 bitumen, which was prepared from

Pasargad Oil Company of Tehran province. The specifications of this bitumen along with the permissible limits of each characteristic are presented in Table 1-3.

2.2. Rubber powder

Rubber powder prepared on the basis of car tape and tube, which is passed through a 50 sieve. In this current research, rubber powder has been used as bitumen additive. Accordingly, a high shear mixer has been used to mix bitumen with rubber powder

and prepare rubber bitumen. Mixing in this machine was at 5000 rpm at a temperature of 170 degrees Celsius for 45 minutes and finally modified bitumen with different percentages of rubber powder was obtained.

Table 1. Specifications of consumed bitumen

Explanation	Results	Test standard	
		AASHTO	ASTM
Maximum wear (%) (Los Angeles method)	20	T96	
Specific gravity (gr/cm ³)	2.654	T85	
Minimum breakage on two sides (%) (on Sieve No. 4)	98		D5821
Maximum water absorption (%) (coarse aggregates)	0.8	T85	
Maximum water absorption (%) (fine aggregates)	1.4	T84	



Figure 1. Rubber powder used in research

2.3.Stone materials

The stone materials used in this research are mountain limestone materials. Consumable materials were obtained from Nokam mine in the southeast of

Tehran province. The specifications of the materials used are presented in [Table 2](#).

Table 2. Characteristics of stone materials

Test	Standard	Results
Softening point	ASTM D-36	47°C
Penetration (at 25°C)	ASTM D-5	67 deci mm
Ignition	ASTM D-92	304°C
Ductility (at 25°C)	ASTM D-113	> 100 CM
Bitumen specific weight	ASTM D-70	1.045 gr/cm ³

2.4. Steel slag

The slag material used in this research is EAF slag, which was obtained from Isfahan Province and Zob Ahan Company. The chemical characteristics of the

steel slag materials used in this research are shown in [Table 3](#).

Table 3. Characteristics of used steel slag

CaO	Fe ₂ O ₃	MgO	Al ₂ O ₃	SiO ₂	SO ₃	TiO ₂	Na ₂ O
33.86	25.75	4.20	4.08	17.54	2.2	1.1	0.4

2.5. Granulation of materials

The materials used in the research (stone materials and steel slag) are graded according to the grading of

the 234th edition of Iranian Roads. The above granularity range is presented in [Figure 2](#).

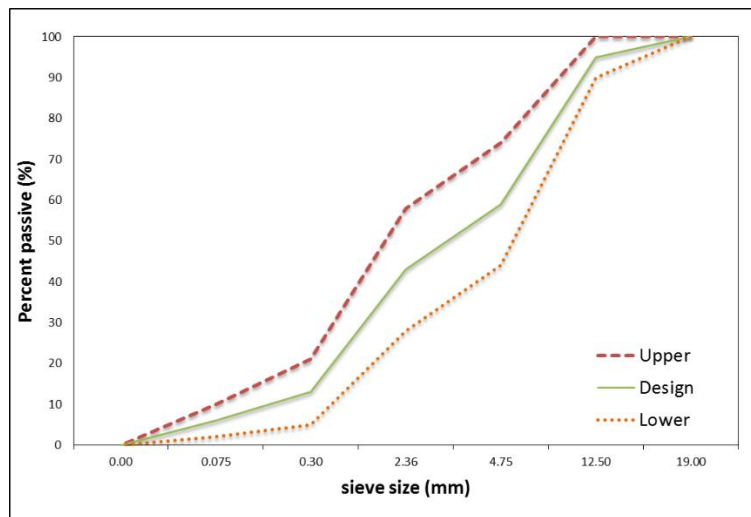


Figure 2. Granulation of stone materials

As mentioned, the grading of stone materials and steel slag is considered the same. But due to the fact that the specific weight of steel slag is different from

that of stone materials, replacing steel slag materials instead of stone materials has been done by volume.

2.6. Case Study

Research samples are classified into four general categories. The first category is the control sample. The second category is samples containing rubber powder, the third category is samples containing

steel slag, and the fourth category is samples containing steel slag and rubber powder. The classification of these samples along with the abbreviations used are presented in [Table 4](#).

Table 4. Composition and mixtures

Abbreviation	steel slag percentage	rubber powder percentage	Number
AC	0	0	1
CR5	0	5	2
CR10	0	10	3
SS50	50	0	4
SS100	100	0	5
CR5SS50	50	5	6
CR5SS100	100	5	7
CR10SS50	50	10	8
CR10SS100	100	10	9

2.7. Fracture toughness

The fracture toughness test in this research has been investigated using the ENDB sample. In this research, ENDB samples were obtained from shearing compacted asphalt mixtures with gyrator. First, cylindrical asphalt mixtures with a percentage of free space of 7% and a diameter of 15 cm and a height of 15 cm were made using a gyratory compactor, and after cooling, three cylindrical

samples with a height of 3 cm and a diameter of 15 cm were made using a cutting machine. Then a 12 mm deep groove is created in the middle of the samples. These samples have been used to determine the fracture toughness in the first loading mode (KIC) and the second loading mode at -12 and -24 temperatures. The fracture test of ENDB samples was carried out under control strain conditions with

a loading rate of 5 mm/min and in three modes of pure tension (mode 1) and pure shear (mode 2). In order for the samples to reach the test temperature,

3. RESULTS AND DISCUSSION

The response variable in this investigation is the value of fracture toughness in different modes. Accordingly, the results are presented in the following four general categories:

- First group: fracture toughness in mode one at -12°C temperature for 9 different research mixing plans
- Second category: fracture toughness in mode one at -24°C temperature for 9 different research mixing designs.

the samples were kept for at least 12 hours in the chamber with the test temperature and then they were tested using the UTM-25 device.

- Third category: fracture toughness in mode two at -12°C temperature for 9 different research mixing designs.

- Fourth category: fracture toughness in mode two at -24°C temperature for 9 different research mixing plans

Each of these categories separately has final data charts, which are presented below and the results are explained.

3.1. Fracture toughness in the mode I at -12

The mode I of loading is called unfolding mode or pure tension mode. In this mode, the support place has the same distance on both sides of the crack as

shown in the third chapter. The results related to fracture toughness in the first loading mode are presented in [Figure 3](#).

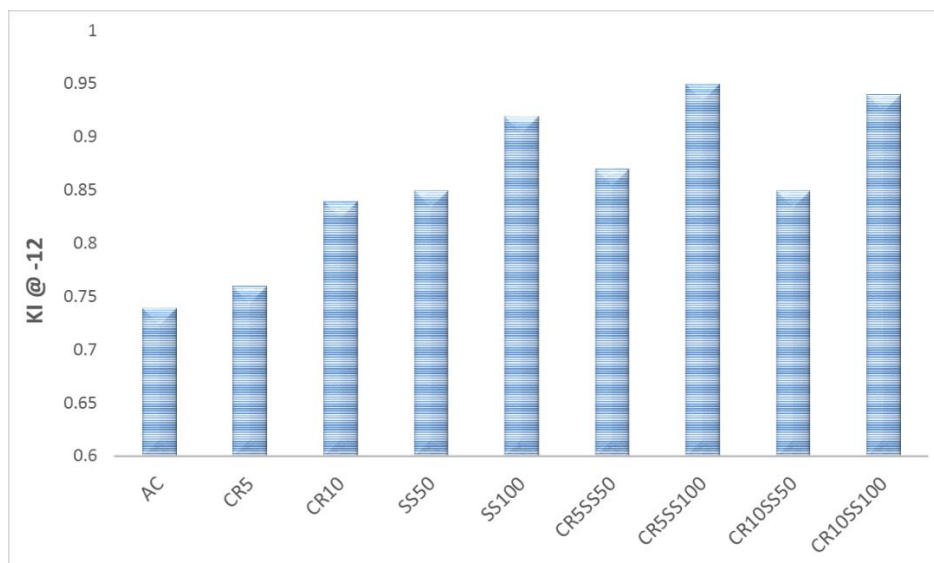


Figure 3. Fracture toughness in the mode I of loading and temperature -12

As you can see from the results, research samples should be considered in the following three categories:

The first category includes samples containing rubber powder as a bitumen additive.

The second category includes samples containing steel slag as a substitute for stone materials.

The third category includes samples containing rubber powder as bitumen additive and steel slag as substitute for stone materials.

As it can be seen from the graph, in the first category, the addition of rubber powder has increased the

fracture toughness in the mode I of loading and temperature of -12 degrees Celsius. This increase has significantly increased with the amount of rubber powder reaching 10%, and among the two examined samples (5 and 10% rubber powder), the samples containing 10% rubber powder have obtained higher fracture toughness.

In the second category, the addition of steel slag compared to the control sample has increased the fracture toughness more significantly than the first category (amendment with rubber powder). In this

category, the samples containing 100% steel slag have the highest fracture toughness values.

In the third category, which has additives and modifiers in both bitumen and stone materials, we see the highest fracture toughness compared to the control sample and the other two categories. Among

these samples, the sample containing 100% steel slag and 5 and 10% rubber powder obtained the highest fracture toughness. However, the sample containing 5% rubber powder and 100% steel slag has slightly higher failure toughness than the other sample.

3.2. Fracture toughness in the mode I and temperature -24

In terms of the type of loading, this sample is the same as the previous samples, but the difference between these samples and the previous samples is the test temperature. This series of samples have been tested at a more negative temperature, and as stated

in the previous sections, the test temperature of these samples is -24 degrees Celsius.

The results related to the fracture toughness of the samples containing the additives of this research in the mode I of loading and the temperature of -24°C are presented in [Figure 4](#).

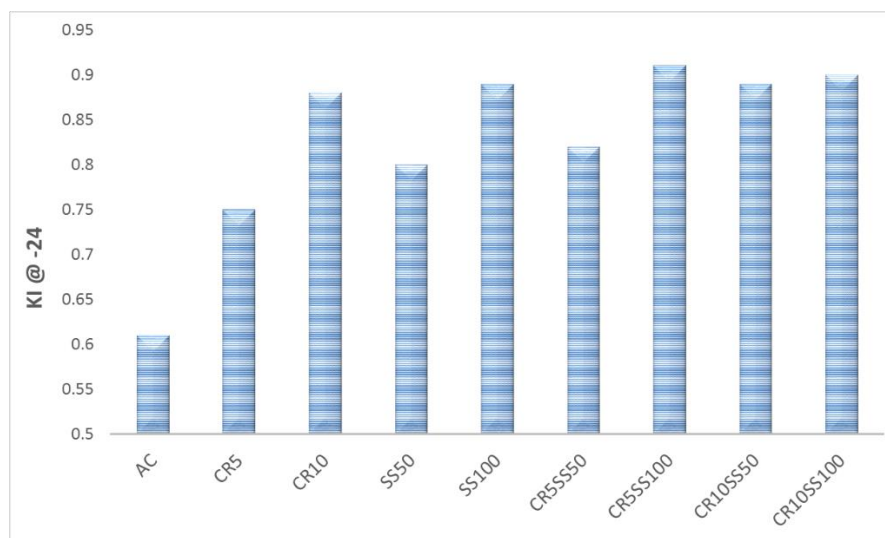


Figure 4. Fracture toughness in the mode I of loading and temperature -24

As it can be seen from the graph, there are three separate groups in the results that were considered in the section of fracture toughness in the mode I and temperature of -12°C in this series of samples.

As it can be seen from the diagram in [Figure 4](#), the addition of rubber powder and steel slag has both increased the fracture toughness in the mode I of loading and temperature of -24 degrees Celsius. But this increase and improvement has a different process, which has been discussed in the following. In the first group of samples, we see a significant increase in the fracture toughness of the samples containing 5 and 10% rubber powder compared to the control sample. Although between these two samples, the value of fracture toughness has experienced a significant increase, the sample

containing 10% rubber powder has shown a higher fracture toughness difference.

In the second category of samples, i.e. samples containing 50 and 100% steel slag, a significant improvement can be seen compared to the control sample, and the amount of this improvement is greater in the sample containing 100% steel slag.

In the third category, three samples, including samples containing 2% rubber powder and 100% steel slag, as well as 10% rubber powder and 50 and 100% steel slag, have obtained the fracture toughness values close to each other. However, among the samples of the third category, the sample containing 5% rubber powder and 100% steel slag has the highest value of fracture toughness in the mode I of loading and temperature of -24 degrees Celsius.

3.3. Fracture toughness in the mode II and temperature -12

The mode II of loading is called pure shear mode or sliding mode. In this mode, the crack faces slide relative to each other in the direction of passing over the crack edge. This mode is caused by shear loading in the crack plane.

The results related to the second loading mode of fracture mechanics at the temperature of -12°C are shown in [Figure 5](#) for 9 different research mixing designs, including samples containing rubber powder, steel slag and the combination of rubber powder and steel slag.

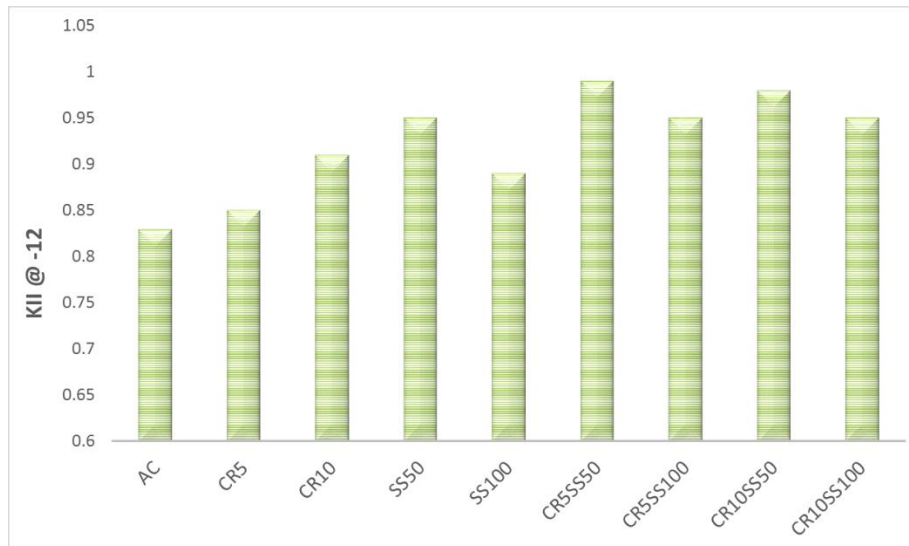


Figure 5. Fracture toughness in the mode II of loading and temperature -12

As it can be seen from the results of [Figure 5](#), the addition of rubber powder at a percentage of 5% has partially increased the fracture toughness. However, adding 10% rubber powder has shown a more significant effect.

The samples containing 50 and 100% of steel slag in the mode II of loading showed a different fracture toughness value compared to the mode I of loading. In the second loading mode, the sample containing 50% steel slag compared to the control sample shows a significant increase in the fracture toughness of the sample, but the sample containing 100% did not continue this growth trend. Although the fracture toughness value of the sample containing 100% steel slag shows an increase compared to the control sample, the fracture toughness of this sample is lower than the sample containing 50% steel slag.

In the samples containing rubber powder bitumen modifier and steel slag stone material modifier, the highest fracture toughness was related to the sample containing 5% rubber powder and 50% steel slag.

However, all the samples of this group have shown a significant increase compared to the control sample.

Fracture toughness in the mode II and -24 temperature

As stated in the previous parts of the research, the research samples were tested at -12 and -24 degrees Celsius and two loading modes, and in this part, which is the last part of the results, the results related to The fracture toughness in the mode II of loading and the test temperature of -24°C is presented for different research samples that include bitumen modifier or stone material modifier or both. The results related to this state of research are presented in [Figure 6](#).

As can be seen from the graph, all modified samples have reported an increase in fracture toughness compared to the control sample. However, this increase and its amount is different in different samples.

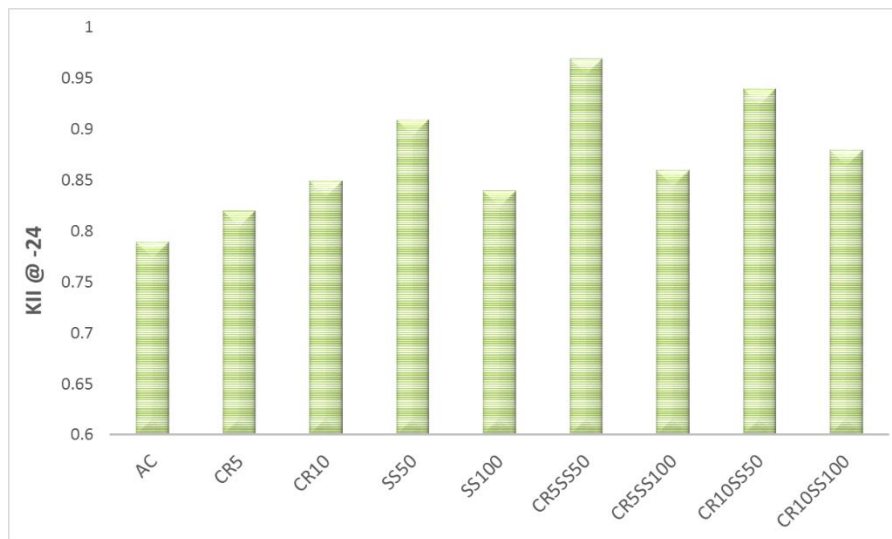


Figure 6. Fracture toughness in the mode II of loading and temperature -24

The diagram in [Figure 6](#) shows that among the two samples containing 5 and 10% rubber powder, both samples had higher fracture toughness than the control sample and the upward trend in the fracture toughness increased with the increase in the amount of rubber powder.

In the samples containing 50 and 100 percent of rubber powder, a similar thing happened with the mode II of loading and the temperature of -12 degrees Celsius, and with the increase in the amount of steel slag from 50 to 100, the upward trend in the fracture toughness value stopped and decreased.

4. CONCLUSION

In this research, the use of recycled materials in asphalt mixtures has been discussed. Accordingly, two recycled materials, recycled asphalt chips and rejuvenator from waste engine oil, have been used. Also, to complete the weaknesses of these two additives, a multi-component fiber has been used.

In order to determine the performance value of research additives and also to determine the optimal amount of use of these additives, the method of optimal mixing design was used in this research. In this plan, the three main failures including rutting, cracking and moisture sensitivity were determined. Further, the tests related to each failure include dynamic creep test to determine rutting, indirect tension test and TSR parameter to determine moisture sensitivity and index test. Illinois ductility was determined for corrosion cracking at intermediate temperatures. In the following, the standard samples of each test were made using a gyratory compaction device. Finally, the samples were evaluated and the optimal samples were

However, the sample containing 100% steel slag had a higher fracture toughness value than the control sample.

Among the samples that have both bitumen modifier and stone material modifier, the sample containing 5% rubber powder and 50% steel slag has the highest fracture toughness. Among these samples, the above sample has obtained significantly higher fracture toughness, which shows that this sample is more resistant to cracking compared to other research samples.

selected using the optimal minimums of the balanced mixing design method.

On this basis and with the explanations presented, the main results of this research showed that:

1. The results of the fracture toughness test in the mode I of loading and the temperature of -12 degrees Celsius showed that the addition of rubber powder and steel slag increases the fracture toughness value, although the combined addition of these materials had a greater effect.
2. Examining the results of the fracture toughness in the mode I of loading and the temperature of -24°C has shown a general trend similar to the temperature of -12°C, but the value of the fracture toughness of each of the mixes compared to the control temperature of -12 There has been a significant reduction.
3. The results of the fracture toughness test in the second pure mode showed that the rubber powder added in both percentages shows an increase in the fracture toughness value, but the samples

containing steel slag in 50% replacement showed better results than the samples containing 100%. They have shown steel slag.

4. Examining the results of all four cases investigated in this research shows that although the addition of 10% rubber powder only improves the fracture toughness more than 5% rubber powder, but when rubber powder is used next to

steel slag. Adding 5% rubber powder will have a more significant improvement.

5. Among the 9 mixing plans investigated in the current research, considering the 5 results, the mixing plan containing 5% rubber powder and 50% steel slag can be introduced as the optimal mixing plan.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts

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